SUSTAINABLE SOLUTIONS: EDIBLE MILLET TABLEWARE AS A SUBSTITUTE FOR SINGLE-USE CUTLERIES IN THE FOOD SERVICE SECTOR

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Synopsis submitted to

Avinashilingam Institute for Home Science and Higher Education for Women,

Coimbatore – 641043

In Partial Fulfilment of the Requirements for the Degree of

Doctor of Philosophy in Food Science and Nutrition

December 2024

A. THESIS TITLE

SUSTAINABLE SOLUTIONS: EDIBLE MILLET TABLEWARE AS A SUBSTITUTE FOR SINGLE-USE CUTLERIES IN THE FOOD SERVICE SECTOR

B. INTRODUCTION

Packaging is essential for preserving food quality, enhancing appeal and convenience, and providing protection and information, but synthetic plastic packaging creates environmental concerns due to its non-biodegradability, pollution, and potential migration of harmful substances into food. The widespread use of Single-Use Plastics (SUP) in the food industry has escalated plastic waste, threatening ecosystems and biodiversity, with only 9% of the 300 million tons of annual plastic waste being recycled. To address these challenges, innovative solutions like edible plant-based packaging made from seaweed, rice bran, and potato starch are being developed, offering biodegradable, sustainable alternatives that extend food shelf life and reduce environmental impact (Chen *et al.,* 2021; Kabir *et al*., 2022; UNEP, 2021).

Eco-friendly and edible packaging offers a sustainable solution to combat plastic pollution, with millets showing significant potential for economic and environmental benefits (Anal *et al*., 2024). Edible cutlery made from ingredients like millets, cereals, soy protein isolate, and fruit peels has been successfully developed using traditional baking methods, providing nutritious, non-toxic, and sustainable alternatives to SUP (Jaspal *et al*., 2024; Nehra *et al*., 2024; Wulandari *et al*., 2023).

This study aims to standardized edible millet tableware from pearl millet and sorghum with antioxidant-rich edible flowers to enhance the nutritional value, sensory appeal, functional and textural properties. This research addresses the pressing need to replace non-biodegradable disposable tableware by formulating and standardizing scalable methods for producing high-quality edible cups and cutlery, aligning with consumer demand for natural, healthy, and sustainable products.

C. SCOPE OF THE STUDY

This study focuses on the development of innovative, edible and ecofriendly millet-based tableware, including cup, bowl, katori, spoon and plate, designed using unique molds to promote sustainable practices in the food service sector. By utilizing native and abundantly available major millets like sorghum and pearl millet, processed through preliminary processing techniques such as germination and roasting. The study enhances the nutrient profile, sensory appeal, and functional and mechanical properties of millet tableware by incorporating selected native antioxidant-rich edible flowers. This pioneering approach aims to provide a viable alternative to single-use plastics, which pose significant environmental challenges. Safety assessments, including cell line studies and brine shrimp lethality assays, confirm its low toxicity. This comprehensive study demonstrates the feasibility of millet-based tableware as a sustainable and innovative solution to reducing the environmental impact of SUP's, offering a pathway toward eco-conscious consumer choices in the food service industry including hospitality, entertainment, airlines, and catering services.

D. OBJECTIVES

The specific objectives of the study are,

- Identification and selection of native, nutrient-rich, cost-effective major millets and edible flowers rich in antioxidant.
- Formulation and Standardization of Millet Tableware.
- Enhancing the functionality of standardized millet tableware by selected flower powder.
- Characterization of Standardized Flower-Enriched Millet Tableware.
- Shelf-life, toxicity and degradability analysis of the Standardized Millet Tableware.

E. METHODOLOGY

Approval from the Institutional Human Ethical Committee and plant authentication (approval number: AUW/IHEC/FSN-21-22/XPD-31) was obtained from The Rapinat Herbarium and Centre for Molecular Systematics (RHT) at St. Joseph's College in Tiruchirappalli, India. The methodology consists of five phases as follows,

Phase I

i. Selection of Major Millets

Pearl millet (*Cenchrus americanus* (L.) Morrone) and sorghum (*Sorghum bicolor* (L.) Moench) are among the most widely cultivated millets in India, accounting for 62% and 26% of the country's total millet production, respectively (APEDA, 2023). Millet-based tableware, made from these cost-effective and nutrient-dense crops, offers a durable and eco-friendly alternative with the added benefit of enhanced nutritional value. For the study, pearl millet and sorghum were purchased from a local market and utilized in three forms - unprocessed, germinated, and roasted. Whole pearl millet and sorghum grains were carefully washed, cleaned, and sorted to remove husk and impurities. The grains were then wrapped in a muslin cloth for germination for 35 hours. Roasting was done by heated in an iron pan for 12 minutes at 90°C until a few grains popped. The unprocessed and processed grains were ground into fine flour using a milling machine and sieved through 0.3 mm mesh and stored in air-tight container.

ii. Property Analysis of Major Millets

Property analysis of unprocessed, germinated and roasted millets was done. Quality of grains through, length, breadth, length/breadth ratio, thickness, thousand grain weight and volume were assessed Khatoniar and Das, (2020), Technological properties like bulk density, swelling capacity (%), water absorption capacity (ml/g), and oil absorption capacity (ml/g) were determined by using the procedure of Khatoniar and Das, (2020). Anti-nutritional factors including tannins, total phenolic content, saponin, and phytic acid levels were measured using standard methods (Sadasivam and Manickam, 2023), optical properties by laboratory scale Colour Reader and functional properties (FTIR, XRD) of flour were evaluated.

Phase II

i. Formulation and Standardization of Millet Tabbleware

The study focused on the formulation, standardization, and characterization of edible tableware including cup, bowl, katori, spoon, and plate from pearl millet and sorghum in unprocessed, germinated and roasted forms. Different combinations and permutations were trialed to standardize the millet tableware. All the formulated tableware were validated for their structural integrity, porous nature, and appearance, and the best proportions were optimized for further enhancement and extensive characterization. Variations I, II, and III of unprocessed and roasted tableware, as well as the first four variations of germinated tableware showed high

porosity that infers the ability to hold liquids for longer durations. Variation IV in unprocessed and roasted millet and Variation V in germinated millet tableware were thick, stable, and non-porous were the selected prime variation.

ii. Characterization of Millet Tableware

The standardized millet-based tableware was thoroughly analyzed for nutritional content, sensory appeal, optical attributes, functional properties, and texture. Nutritional evaluation included moisture, ash, protein, fat, crude fiber (AOAC standards), carbohydrates (anthrone method), and key micronutrients like vitamin C, iron, calcium, and phosphorus using volumetric and titration methods (AOAC, Sadasivam & Manickam, 2023). Optical properties were assessed using a laboratory-scale color reader, and sensory evaluation was conducted with a 9-point hedonic scale by 30 semi-trained panelists. Functional analyses involved FTIR (Shimadzu MIRacle10), thermogravimetric analysis (EXSTAR/C300), exposure testing, and a 40-minute water absorption test (Nehra et al., 2024). Textural properties, including hardness, elasticity, and drop resistance, were measured using the Shimadzu EZ-XS texture analyzer and standardized drop tests. The optimal variation for further functional improvements was selected based on exposure, water absorption, and texture test results.

Phase III

i. Selection and Processing of Edible Flower

Four edible flowers such as (*Moringa oleifera* Lam.), hibiscus (*Hibiscus rosa-sinensis* L.), rose (*Rosa damascena* Herrm.) and agathi (*Sesbania grandiflora* (L.) Poir.) were selected based on their well-documented nutrient profile, antioxidant properties, and local availability. The flowers were collected during their peak blooming season in January to March from the Karur district of Tamil Nadu. Fully bloomed white agathi flowers, red five-petal hibiscus flowers, whitish moringa flowers, and pink damask roses were harvested in the morning, between 8 a.m. and 9 a.m. to ensure freshness. After harvesting, the flowers were cleaned, petals were separated, shade-dried and ground into a fine powder.

ii. Characterization of Edible Flower

Nutrient content, phytochemical profile, antioxidant activity (DPPH method), optical properties, FTIR, and microbial stability of the flower were analysed. The high-profile flowers were selected and incorporated into standardized unprocessed and roasted pearl millet and sorghum tableware (cup, bowl, katori, spoon, and plate), to enhance both the functional and aesthetic qualities.

Phase IV

i. Formulation, and Standardization of flower-enriched Millet Tableware

Based on the results obtained from Phase 2 and Phase 3, unprocessed and roasted pearl millet and sorghum were identified as the suitable best formulation and functionally enriched with hibiscus and rose flower then subjected to characterization. The formulation for flower enriched millet tableware was combined with a mixture of millet flour, flower powder, binders, water, and refined sunflower oil in specific ratios to optimize nutritional content, antioxidant activity, structural integrity, and durability. The selected proportions underwent a standardized baking process, where the cup and spoon were baked at 70°C, while the bowl, katori, and plate were baked at 90°C. The baking durations were between from 8 to 20 minutes, depending on

the variation (unprocessed, germinated, or roasted) and the type of tableware (sorghum or pearl millet). The addition of shade-dried edible flower powder did not alter the required baking time or temperature.

ii. Characterization of Flower-enriched Millet Tableware

The Flower-enriched Millet Tableware was characterized by, nutrient analysis, sensory evaluation, antioxidant activity, optical properties, functional properties (FTIR, TGA, Exposure test and Water Absorption Test) and textural properties (Hardness force, elastic force and drop test).

Phase V

i. Shelf-life Evaluation of Millet Tableware

Total microbial count by Serial Dilution Method, along with weight and moisture changes, was monitored over 120 days of storage in airtight containers at room temperature to evaluate the shelf life of the millet tableware.

ii. Toxicity Analysis of Millet Tableware

In-vitro cell line studies and in-vivo brine shrimp lethality assay was done for toxicity analysis.

For in-vitro cell line studies, L-929 fibroblast cells (mouse connective tissue) were obtained from NCCS, Pune, and cultured in DMEM medium supplemented with 10% FBS and antibiotics in a CO2 incubator (5% CO2, 95% humidity). Cytotoxicity tests were performed in 96-well plates under controlled atmospheric conditions using the Innova CO-170 incubator.

The brine shrimp lethality assay for standardized pearl millet and sorghum tableware was conducted at five concentrations (100–1500 µg/ml) using brine solution as a blank and potassium dichromate as a positive control. Mortality was observed at intervals of 1, 2, 4, 6, and 24 hours after introducing 30 brine shrimps into 25 ml of the sample.

iii. Degradability Analysis of Millet Tableware

2 g piece of tableware was buried 10 cm deep in wet topsoil within a beaker and monitored until complete degradation. Samples were retrieved on the 3rd, 6th, and 9th days, then dried in a hot air oven at 70°C for 24 hours.

iv. Cost Calculation of Millet Tableware

The cost of the final product was estimated by accounting for direct expenses like millet procurement, edible flowers, and transportation, as well as processing, manpower, and overhead costs, including indirect labor and materials.

The obtained results were analyzed using One-way ANNOVA with 5 % level of significance.

F. ORIGINAL CONTRIBUTIONS

The salient findings of the study are as follows,

Phase I - Property Analysis of Selected Major Millets

i.Quality of Millet and Flour

The physical and functional characteristics of pearl millet and sorghum grains and flour differ significantly. Sorghum grains are larger and thicker than pearl millet. Sorghum also has greater grain volume than pearl millet.

Processing methods significantly impact grain quality and flour yield. Germination increases flour yield (up to 94% in PMGG and 92.6% in SGG) due to better water retention, while roasting reduces yield due to moisture loss but enhances water and oil absorption

capacities. Germination lowers bulk density, increases moisture content, and decreases absorption capacities, whereas roasting maintains lower moisture levels while improving functional properties. These variations underscore the importance of processing in determining grain quality and usability.

ii. Anti-nutritional Factor and Properties of Flour

Anti-nutritional factors showed that, germination generally reduces antinutritional factors like phytic acid, tannins, and saponins, while roasting enhances total phenol content, making these processes suitable for improving the bioavailability and functionality of these grains in millet tableware formulations. Processing pearl millet and sorghum considerably lowered phytic acid and tannin levels ($p < 0.05$).

iii. Optical and Functional Properties of Flour

The optical properties showed that, germinated and unprocessed sorghum flours indicated minimal colour change (ΔE). The findings highlight the impact of processing methods on the colour attributes of pearl millet and sorghum flours, with roasting inducing pronounced changes due to chemical reactions, and germination leading to lighter and less intense coloration.

The FTIR spectra of unprocessed, germinated, and roasted pearl millet and sorghum flours reveal significant compositional and structural differences. Unprocessed flour shows characteristic peaks for hydroxyl, amine, and aliphatic hydrocarbon groups, with a strong signal for ester or aldehyde groups at 1743 cm^{-1}. roasted flour exhibits broader O–H stretching peaks, indicating stronger hydroxyl interactions or hydrogen bonding, and distinct peaks in the fingerprint region (995.27, 856.39, 648.08 cm^{-1}), suggesting better-organized structural features. Germinated flour displays sharper peaks at 1080.14 and 439.77 cm^{-1}, reflecting unique molecular arrangements. These variations highlight distinct structural and molecular characteristics among the samples.

X-Ray Diffraction indicated, the unprocessed millet flour had the highest crystallinity with sharp, well-defined peaks, whereas germinated millet flour exhibited reduced crystallinity due to structural disruption of double helices. Roasted millet flour increased the crystallinity, resulting in intermediate crystal sizes and sharper peaks than germinating samples, indicating that thermal processing promotes molecular packing and structural organization.

TGA of millet flour showed that in pearl millet, by the end of the thermal process, total weight losses were 94.3% for unprocessed flour, 91.5% for germinated flour, and 93.8% for roasted flour, leaving residues of 0.20 mg, 0.46 mg, and 0.28 mg, respectively. In sorghum flour, total weight losses reached 85.2%, 89.5%, and 88.3%, leaving final residues of 1.18 mg (14.8%), 0.83 mg (10.5%), and 0.78 mg (11.7%) for the unprocessed, germinated, and roasted flours, respectively. This shows that pearl millet undergoes more thermal degradation as compared to sorghum flour.

Phase II - Characterization of Standardized Millet Tableware

i. Physical Properties of Millet Tableware

The weight of the standardized millet tableware varied and processing of millets plays a vital role. The average weight of the cup, bowl, katori, spoon and plate were 16.56 ± 0.15, 19.43 ± 0.05, 19.87 ± 0.05, 8.09 ± 0.02 and 47.71 ± 0.03 respectively.

ii. Nutrient Analysis of Millet Tableware

Nutrient analysis revealed distinct differences between sorghum and pearl millet tableware. Sorghum tableware had higher moisture and ash contents, with germinated sorghum showing the highest levels. Carbohydrate content was greater in sorghum, especially in roasted forms, while roasted pearl millet also displayed significant carbohydrate levels. Roasted pearl millet tableware had the highest protein and fiber content, whereas sorghum had lower fat levels, particularly in germinated and roasted forms. Fiber was more abundant in pearl millet, especially in unprocessed and roasted samples. Vitamin C was slightly higher in germinated sorghum, while germinated pearl millet had the highest iron levels. Calcium was relatively consistent across all samples, with germinated forms slightly elevated, and phosphorus was most abundant in pearl millet-based cups. Overall, roasted pearl millet excelled in protein and fiber, while sorghum stood out for carbohydrates and micronutrient content.

iii. Sensory Evaluation of Millet Tableware

Sensory evaluation of the standardized millet cup, bowl, katori, spoon and plate showed a score between 6.5 to 8.9 that falls under like slightly to like extremely category. All the tableware were standardized in a unique mold; hence the shape or appearance are uniform and scored above 7. The colour of roasted were darker scored less as compared to germinated and unprocessed counterparts exhibiting lighter shade. Similar pattern was found in taste, flavour and crispiness preferences, indicating germinated tableware scored better as compared to unprocessed and germinated counterparts. The overall acceptability of all the tableware falls under like moderately to like extremely category.

iv. Thermal Analysis of Millet Tableware

TGA of millet tableware found that, a total degradation of 72.6%, 88.8%, and 100% in unprocessed, germinated and roasted pearl millet tableware and 82.8%, 99.8%, and 100.3% in unprocessed, germinated and roasted sorghum tableware was observed respectively. This shows that sorghum tableware undergoes more thermal degradation than pearl millet.

v. Exposure test and Water Absorption rate of Millet Tableware

Exposure tests of millet-based tableware showed that roasted pearl millet and sorghum cup held ambient and hot water for 30 minutes without leakage, while unprocessed and germinated variants lasted 10–20 minutes. All cup resisted leakage with ice exposure for up to an hour. Bowl, katori, and plate made from unprocessed and roasted millets showed no absorption at ambient temperature for 40 minutes, while germinated variants lasted 30 minutes. At hot temperature, germinated versions absorbed water after 20 minutes, unprocessed after 25 minutes, and roasted remained unaffected for 30 minutes. At cold temperature, all tableware absorbed negligible water for up to 60 minutes. For spoon, roasted millet variants held ambient and hot water for 30 minutes, while unprocessed and germinated versions lasted 20 and 17 minutes, respectively. At cold temperature, all spoons resisted water absorption for 60 minutes but softened slightly thereafter. Water absorption tests indicated that pearl millet absorbed more water than sorghum across all temperatures, with germinated tableware being more absorbent than roasted and unprocessed counterparts.

vi. Texture analysis of Millet Tableware

The texture analysis of pearl millet and sorghum-based cups, bowls, katori, spoon, and plates revealed significant variations influenced by processing methods. Germinated tableware generally exhibited the lowest hardness and elasticity, indicating softer textures, while roasted

variations consistently demonstrated enhanced hardness and structural strength. For cups, germinated pearl millet (PMGC) and sorghum (SGC) were the softest, while roasted sorghum (SRC) had the highest elasticity. Among bowls, roasted sorghum (SRB) displayed superior hardness and elasticity, significantly outperforming unprocessed and germinated versions. In katori, roasted pearl millet (PMRK) showed the best mechanical properties, while germinated katori were weakest. For spoons, roasting improved elasticity, as seen in roasted pearl millet (PMRS), though germination increased hardness. In plates, roasting enhanced hardness, while unprocessed plates retained the highest elasticity. These results confirm that processing methods such as roasting and germination significantly impact the mechanical properties of millet-based products, with roasting generally enhancing structural resilience.

Drop test showed that, sorghum-based products consistently outperformed pearl millet variants, particularly in their roasted forms, which exhibited the highest durability. Among pearl millet items, unprocessed versions generally resisted cracks and breakage better than germinated and roasted ones. The results suggest that roasted sorghum products are better suited for applications requiring greater structural integrity, while pearl millet variants may offer more flexibility in applications where moderate durability suffices.

vii. Selection of Prime Variation of Millet Tableware for further enhancement

By considering the results obtained from the properties including water absorption rate, exposure test, textural analysis and drop test, the unprocessed and roasted pearl millet and sorghum proportions of the cup, bowl, katori, spoon, and plate were selected for further enhancement after the functional and mechanical property examination. Conversely, the variants of germinated pearl millet and sorghum were not included in the subsequent flower powder enrichment and characterization as they showed the least properties.

Phase III - Property Analysis of Edible Flowers

i. Nutrient Analysis of Edible Flower

Moringa flower powder (MFP) had the highest moisture (8.9%), protein (5.85 g), vitamin C (108.66 mg), iron (3.85 mg), and calcium (82.7 mg) content, while rose flower powder (RFP) led in carbohydrates (15.08 g) and fiber (8.92 g). Hibiscus flower powder (HFP) had the highest fat content (4.21 g) but the lowest protein (1.23 g), vitamin C (7.93 mg), iron (0.98 mg), and calcium (3.76 mg). Agathi flower powder (AFP) showed the highest ash content (9.77%) and the lowest fat content (2.38 g). These differences were statistically significant ($p < 0.05$), highlighting distinct nutritional profiles for each flower powder.

ii. Phytochemical Screening of Edible Flower

Hibiscus flower powder displayed the most diverse phytochemical profile, consistently present across nearly all solvents. Moringa flower powder was rich in amino acids, carbohydrates, phenols, glycosides, and tannins but lacked anthocyanins and terpenoids. Rose flower powder also had a strong phytochemical presence, including alkaloids, flavonoids, and tannins, though slightly less consistent than HFP. Agathi flower powder showed good levels of amino acids, carbohydrates, and phenols but had weaker levels of alkaloids, anthocyanins, and tannins. Overall, HFP and RFP were the most diverse, while AFP and HFP demonstrated more selective profiles, making them suitable for specific applications.

iii. Antioxidant Activity of Edible Flower

The IC50 values highlighted RFP have strong antioxidant activity (15.76 µl/ml), followed by HFP (54.92 µl/ml), AFP (78.09 µl/ml), and MFP (139.88 µl/ml). Hence, hibiscus

flower powder (HFP) and rose flower powder (RFP) exhibited the better antioxidant activity which is taken for further enhancement in standardized millet tableware.

iv. Total Microbial Load of Edible Flower

Moringa flower powder (MFP) exhibited the highest microbial growth, starting at 4×10^{-1} CFU on day 30 and reaching 24×10^{-1} CFU by day 120. Hibiscus (HFP), rose (RFP), and agathi (AFP) flower powders showed lower initial counts of 2×10^{-1} CFU on day 30. By day 120, RFP had the lowest microbial count (13×10^{-1} CFU), followed by HFP and AFP. Overall, RFP and HFP demonstrated better microbial stability, suggesting their suitability for extending the shelf life of millet tableware.

v. Selection of Edible Flower for further enhancement

A comprehensive evaluation of hibiscus (HFP), rose (RFP), moringa (MFP), and agathi (AFP) flower powders highlighted their unique nutritional, phytochemical, antioxidant, and microbial properties. HFP and RFP emerged as standout candidates for enhancing millet-based tableware due to their superior antioxidant activity, and microbial stability over a 120-day period. These findings affirm the suitability of HFP and RFP for incorporation into unprocessed and roasted pearl millet and sorghum tableware (cups, bowls, katori, spoons, plates), enhancing their functional, aesthetic, and shelf-stability qualities.

Phase IV - Characterization of Flower Enriched Millet Tableware

i. Nutrient Analysis of Flower Enriched Millet Tableware

The nutrient analysis of pearl millet and sorghum flower-enriched tableware reveals significant improvements with roasting and flower incorporation. Moisture content ranges from 3.20% to 4.10%, with roasted samples generally higher. Carbohydrate levels increase notably in roasted and flower-enriched variants, peaking at 77.72 g in roasted sorghum with rose. Protein content also improves, reaching 12.19 g in roasted hibiscus-enriched sorghum. Fiber content is consistently elevated in flower-enriched samples, with hibiscus and rose showing the highest values (12.42–13.7 g). Fat content moderately increases with roasting, and vitamin C remains low across all samples (0.27–0.39 mg). Iron and phosphorus levels significantly improve with roasting and enrichment, peaking at 7.46 mg and 206.26 mg, respectively. Calcium content shows minimal variation (32.34–34.44 mg). These findings demonstrate the enhanced nutritional value of roasted, flower-enriched tableware, particularly in carbohydrates, protein, fiber, and iron, making it a sustainable and nutrient-dense option.

ii. Antioxidant activity of Flower Enriched Millet Tableware

Both pearl millet and sorghum tableware demonstrate strong antioxidant activity, and sorghum exhibits greater inhibition at lower doses, as indicated in its lower IC50 values (SURT: 39.87 µg/ml). Rose excels hibiscus in sorghum, whereas hibiscus dominates pearl millet. Flower-enriched unprocessed samples are high in IC50 efficiency followed by roasted variations, emphasizing the antioxidant property of flower inclusion.

iii. Optical Properties of Flower Enriched Millet Tableware

The optical properties of pearl millet and sorghum-based edible tableware are significantly influenced by processing (roasting) and flower enrichment (hibiscus and rose powders). Roasted samples exhibited higher lightness (L*), with values ranging from 12.35 to 16.35 in pearl millet and 9.74 to 14.57 in sorghum, due to the Maillard reaction and pigment retention. Red-green spectrum (a*) values showed subtle variations, with pearl millet having lower red tones (0.39–1.62) and sorghum exhibiting slightly higher values (1.38–4.01) in

unprocessed samples. Yellow hues (b*) were enhanced in roasted and flower-enriched samples, with values reaching 8.32 in pearl millet and 7.53 in sorghum, attributed to caramelization and stable pigments. Total color differences (ΔE) were most pronounced in roasted samples (10.3 for pearl millet and 8.18 for sorghum), reflecting the combined effects of roasting and flower incorporation. Statistically significant F values ($p < 0.05$) confirm the role of these processes in creating visually appealing and sustainable tableware.

iv. Sensory Evaluation of Flower Enriched Millet Tableware

Sensory evaluation revealed that both pearl millet and sorghum-based bowls, plates, and spoons were well-received, with unprocessed and roasted variants scoring highest in taste, flavor, and overall acceptability. Roasting consistently enhanced visual appeal, shape, crispiness, and consumer preference, emerging as the most favorable processing method. While flower enrichment, such as rose and hibiscus, introduced unique sensory attributes, their overall acceptance was moderate, with opportunities for optimization in flavor and color. Despite slight declines in sensory ratings after flower enrichment, all variations remained within the "liked very much" to "liked moderately" range. Both millet types showcased strong potential as innovative, sustainable, and functional tableware options with versatile applications

v. FTIR of Flower Enriched Millet Tableware

The FTIR spectra of pearl millet and sorghum-based tableware reveal distinct structural and compositional changes influenced by processing (roasting) and flower powder enrichment (hibiscus and rose). Unprocessed samples show prominent O-H stretching peaks indicative of higher moisture and hydroxyl group content, while roasted samples exhibit reduced moisture and molecular rearrangements, particularly in polysaccharides, lipids, and aromatic compounds. Flower enrichment introduces additional functional group vibrations, with hibiscus contributing peaks associated with aromatic and inorganic compounds, and rose enhancing aromatic ring vibrations and compositional differences. Key spectral shifts in both millet and sorghum samples highlight the effects of roasting, with enriched variants showing unique peaks reflecting interactions with plant-derived pigments and compounds. These spectra underscore how processing and enrichment significantly alter the biochemical and structural properties of the tableware, enhancing its functional profile.

vi. Thermal Analysis of Flower Enriched Millet Tableware

The TGA analysis of flower-enriched pearl millet and sorghum-based tableware demonstrates distinct thermal degradation behaviors influenced by processing (roasting) and flower enrichment (hibiscus and rose). Moisture and volatile losses (20°C–200°C) vary across samples, with roasted variants exhibiting slightly higher values, reflecting reduced hydration. Organic decomposition (300°C–680°C) dominates the second peak, with the highest losses observed in unprocessed flower-enriched millet (74.8% for PMUHT) and roasted sorghum (78% for SRT), indicating high organic content. Minimal inorganic contributions are reflected in modest residues after 700°C, with unprocessed samples retaining slightly more inorganic matter compared to roasted ones. Total mass loss highlights the compositional impact of enrichment and roasting, with pearl millet and sorghum showing significant variations in stability and degradation profiles. Roasted samples exhibit near-complete decomposition, while flower enrichment enhances organic contributions, underscoring the structural and compositional diversity of the tableware.

vii. Exposure test and water absorption rate of Flower Enriched Millet Tableware

The exposure tests of flower-enriched pearl millet and sorghum tableware (cups, bowls, katori, spoons, and plates) reveal their suitability for serving a range of foods and beverages under ambient, hot, and cold conditions. Flower-enriched cups held ambient and hot liquids for 12–25 minutes and cold liquids for 60 minutes, with roasted variants showing slightly better performance. Bowls and katori resisted absorption for 25–40 minutes at ambient and hot temperatures, with no issues under cold conditions for up to an hour. Spoons retained structural integrity for 15–25 minutes in hot liquids and 45 minutes in cold, demonstrating versatility for various culinary tasks. Plates remained stable for 30–40 minutes under ambient and hot conditions and up to 45 minutes for cold foods, making them suitable for dry snacks and small meals. Across all types, flower enrichment slightly reduced water-holding duration compared to unenriched variants but maintained functionality, highlighting their potential as sustainable tableware for diverse food service applications.

viii. Texture Analysis of Flower Enriched Millet Tableware

Texture analysis showed that sorghum tableware was harder than pearl millet tableware, and hibiscus enrichment further enhances hardness in both unprocessed and roasted variants. Roasting generally reduces the hardness of millet bowls but increases elasticity in sorghum bowls. Flower enrichment, particularly with hibiscus, has a significant effect on both hardness and elasticity, depending on the type of millet and processing method. High F-values across all parameters confirm the critical role of processing and flower enrichment in altering the texture and structural integrity of millet tableware.

Roasting significantly enhances the impact resistance of pearl millet and sorghum-based products, including cups, bowls, katori, spoons, and plates, while flower enrichment slightly reduces their durability in unprocessed variants. Unprocessed pearl millet and sorghum cups withstand impacts up to 90 cm before cracking, with breaking occurring at 110 cm, while flower-enriched cups crack earlier at 80 cm and break by 100 cm. Roasted cups, however, resist cracks up to 100 cm and break at 110 cm, with roasted flower-enriched versions showing slightly reduced durability, cracking at 90 cm. Similar trends are observed in bowls, katori, spoons, and plates, where unprocessed versions have lower durability than roasted ones, and flower-enriched variants crack earlier. For instance, unprocessed pearl millet bowls crack at 130–140 cm and break at 150 cm, while roasted bowls resist cracking up to 140 cm and break at 150 cm. Flower-enriched roasted bowls crack earlier but still maintain good durability. Sorghum-based products show comparable trends, with roasted variants outperforming unprocessed and flower-enriched versions in terms of impact resistance. Across all product types, roasting plays a crucial role in enhancing structural integrity, making roasted millet-based products more suitable for applications requiring higher durability, while flower enrichment slightly reduces durability in unprocessed versions.

Phase V - Analysis of Shelf Life, Toxicity, and Biodegradability of Millet Tableware

i. Total Microbial Count of Millet Tableware

Unprocessed millet tableware, such as PMUT and SUT, shows the highest susceptibility to degradation, with PMUT's degradation rising from 2×10^{-1} at Day 30 to 21×10^{-1} at Day 120. Enrichment with hibiscus or rose (PMUHT, PMURT) moderates this increase, but degradation remains significant. Roasted tableware (PMRT, SRT) exhibits superior resistance, with PMRT maintaining minimal degradation, starting at 0×10^{-1} and ending at 8×10^{-1} by Day 120. Roasted

and enriched variants (PMRHT, PMRRT, SRHT, SRRT) also show better stability, with values at or below 8×10^{-1} by Day 120. Sorghum-based tableware experiences slower degradation than pearl millet, with roasting (SRT) proving most effective, showing near-zero degradation across all time points. Overall, roasting, especially when combined with enrichment, significantly improves the stability of both pearl millet and sorghum tableware.

ii. Change in weight and moisture of Millet Tableware

Sorghum and pearl millet tableware samples exhibit gradual weight increases over a 120-day period, with sorghum cups (SUC) showing the highest increase from 16.62 g to 17.12 g, indicating steady moisture absorption, while roasted and hibiscus-enriched sorghum cups (SRC, SRRC, SRHC) show more stable moisture retention with minimal increases. Pearl millet cups (PMUC) demonstrate a slight increase from 16.44 g to 16.83 g, with roasted and hibiscus-enriched variants (PMRC, PMRHC) showing better stability against moisture absorption. Similar trends are observed in bowls, katori, spoons, and plates, where sorghum generally shows lower weight increases than pearl millet. For instance, sorghum bowls (SUB) reach 20.08 g, while pearl millet bowls (PMUB) reach 23.57 g by Day 120. Katori samples show similar trends, with pearl millet katori (PMURK) achieving a slightly higher weight than sorghum katori (SUK). Spoons from both grains also exhibit gradual weight increases, with pearl millet spoons generally maintaining higher weights than sorghum spoons. Plates, however, show more variability, with some pearl millet plates (PMUHP) experiencing slight decreases in weight before increasing again. Overall, roasted and hibiscus-enriched tableware from both grains demonstrate superior stability in moisture retention compared to unprocessed variants, with pearl millet products generally exhibiting higher final weights than sorghum.

iii. Toxicity of Millet Tableware

The cytotoxicity of pearl millet and sorghum-based tableware extracts was evaluated using cell viability assays and brine shrimp lethality tests. Control cells showed 100% viability, while unprocessed millet and sorghum tableware (PMUT, SUT) exhibited a gradual decline in cell viability with increasing concentrations, leading to rising cytotoxicity, from 8.88% to 28.21% for sorghum and from 15.65% to 28.16% for pearl millet. Hibiscus-enriched samples (PMUHT, SUHT) showed more pronounced toxicity at lower concentrations, while rose-enriched variants (PMURT, SURT) had relatively moderate effects. Roasted millet and sorghum tableware (PMRT, SRT) caused a more significant decrease in viability, with the highest cytotoxicity observed in SRT (40.06%). The brine shrimp lethality assay revealed minimal immediate toxicity for all samples at 2 hours, with slight mortality increasing over time, especially in roasted and flower-enriched samples. At 24 hours, pearl millet samples like PMURT and PMRT showed 10% mortality at 1500 µg/ml, while sorghum samples (SUT, SUHT, SURT) exhibited only up to 10% mortality, even at higher concentrations. The brine shrimp assay indicated that both pearl millet and sorghum tableware have low toxicity, with mortality rates generally below 10% at concentrations up to 1500 µg/ml, suggesting that while higher concentrations increase toxicity, both types of tableware exhibit low cytotoxic effects overall.

iv. Biodegradability of Millet Tableware

Unprocessed pearl millet tableware (PMUT) shows significant degradation, dropping from 1.98 ± 0.09 g on Day 1 to 0.51 ± 0.02 g on Day 9, with similar trends observed for PMUHT and PMURT. However, PMURT retains slightly more weight (0.60 ± 0.01 g) on Day

9, likely due to the rose enrichment. Roasted variants (PMRT, PMRHT, PMRRT) also exhibit comparable degradation, with PMRRT maintaining a slightly higher residual weight (0.58 ± 0.03 g) due to its enriched composition. Sorghum tableware follows a similar biodegradability pattern, with unprocessed (SUT) and enriched (SUHT, SURT) variants showing similar reductions as the pearl millet samples, while roasted types (SRT, SRHT, SRRT) retain slightly more weight, particularly SRHT, which exhibits higher residual weight (0.58 ± 0.03 g). Hibiscus and rose enrichment moderately affect biodegradability, likely influencing material composition. Overall, both pearl millet and sorghum tableware are highly biodegradable, with minor variations based on treatment and enrichment.

v. Cost of Millet Tableware

The cost for cups ranges from Rs. 150 for unprocessed to Rs. 165 for flower-enriched, while bowl, katori, spoon, and plate show similar price trends, with flower-enriched tableware consistently costing Rs. 5 to Rs. 10 more than processed, and processed costing slightly more than the unprocessed versions. The price increase from unprocessed to flower-enriched items reflects the added value of processing and enrichment with flower powders.

G. CONCLUSION

The characterization of standardized edible flower-incorporated millet tableware involves a multifaceted evaluation, from nutrient composition and functional properties to mechanical durability and consumer acceptability. The results of these tests highlight the potential of edible tableware as a sustainable alternative to single-use plastic, offering both functional integrity and health benefits due to the inclusion of antioxidant-rich flower powders. These comprehensive characterizations ensure that the tableware is not only eco-friendly but also meets the sensory and structural requirements for practical use in food service applications.

The physical, structural, and nutritional properties of pearl millet and sorghum grains, emphasizing the impact of processing methods such as germination and roasting. Sorghum grains are larger and thicker than pearl millet, with greater weight and volume, while pearl millet exhibits a higher length-to-breadth ratio. Germination enhances flour yield and reduces antinutritional factors, such as phytic acid and tannins, but increases microbial load due to higher moisture retention. Roasting, in contrast, improves water and oil absorption, lowers moisture, and enhances phenolic content. Structural analyses reveal that germination reduces crystallinity and disrupts molecular organization, whereas roasting promotes molecular packing. Thermal analysis shows that pearl millet undergoes greater degradation than sorghum. Optical and microbial studies underscore the effects of processing on color stability and microbial safety, with roasted sorghum flours demonstrating lower microbial loads due to thermal stability. These findings highlight the potential of tailored processing to optimize millet grain functionality and shelf life.

The millet-based tableware made from pearl millet and sorghum, focusing on the effects of processing methods namely, roasting, germination, and unprocessed forms—on their physical, mechanical, and functional properties. Sorghum tableware exhibited higher moisture, carbohydrate, and micronutrient content, while pearl millet excelled in protein and fiber, especially in roasted forms. Roasting enhanced structural strength, durability, and sensory appeal, whereas germination reduced hardness and elasticity but increased water absorption and nutrient bioavailability. Water and thermal exposure tests demonstrated superior performance of roasted tableware, particularly sorghum, in maintaining structural integrity

under varying conditions. FTIR and TGA analyses revealed compositional and thermal stability differences, with roasted products showing improved crystallinity and durability. Drop tests further confirmed the higher resilience of roasted sorghum tableware. Overall, roasted millet formulations emerged as optimal for functional tableware due to their durability, nutrient density, and eco-friendly potential, making them a sustainable alternative to single-use plastics. Germinated forms were excluded from further development due to inferior mechanical properties.

The characterization of flower-enriched millet tableware highlights the impact of roasting and flower incorporation (hibiscus and rose) on its nutritional, sensory, and functional properties. Roasting and enrichment significantly improve the nutritional profile, boosting carbohydrates, protein, fiber, and iron, with hibiscus-enriched variants excelling in fiber and antioxidant activity. Roasting enhances visual appeal, crispiness, and consumer acceptability, while flower enrichment introduces unique sensory attributes but slightly lowers structural durability. FTIR and TGA analyses reveal molecular and thermal changes, with roasting enhancing crystallinity and stability, and flower powders contributing distinct functional groups. Roasted tableware exhibits superior impact resistance, water retention, and mechanical properties compared to unprocessed and flower-enriched versions. Sensory evaluations confirm high consumer acceptance, particularly for roasted variants. Overall, roasted flower-enriched millet-based tableware emerges as a sustainable, nutrient-dense alternative for diverse culinary applications, balancing durability, functionality, and eco-friendly innovation.The analysis of millet-based tableware reveals their biodegradable, low-toxicity, and durable nature, enhanced by roasting and flower enrichment (hibiscus and rose). Unprocessed variants degrade rapidly, with roasted and enriched versions showing greater stability, particularly sorghum-based products. Weight gain from moisture absorption is minimal in roasted and coated samples, indicating better resistance. Cytotoxicity tests show low toxicity overall, with roasted and enriched variants slightly more toxic but still within safe limits. Biodegradability remains high across all treatments, with roasted samples retaining more weight. Cost analysis highlights the affordability of these sustainable tableware options, with slight price increases for processing and enrichment. These findings underscore the practicality and eco-friendliness of millet tableware as a versatile alternative for diverse applications.

H. STRENGTH OF THE STUDY

1. The present study proved that the standardized edible millet tableware could be a better replacement for single use cutleries in food service sector.
2. The characterization of flower enriched millet tableware increases the nutrient profile, antioxidant activity, sensory appeal with better functional and mechanical properties.
3. Edible millet tableware is less toxic with better shelf life for 120 days and easily degradable within 15 days under soil burial test.

I. LIMITATION OF THE STUDY

The study focused on two major millet kinds and four local, low-cost edible flowers, restricting the variety of materials can be investigated.

J. REFERENCES

1. Anal, A. K., Singh, R., Rice, D. L., Pongtong, K., Hazarika, U., Trivedi, D., & Karki, S. (2024). Millets as Supergrain: A Holistic Approach for Sustainable and Healthy Food Product Production. *Sustainable Food Technology*.
2. APEDA, 2024, https://apeda.gov.in/milletportal/Production.html accessed on 01.12.2024.
3. Chen, Y., Awasthi, A. K., Wei, F., Tan, Q., & Li, J. (2021). Single-use plastics: Production, usage, disposal, and adverse impacts. *Science of the total environment*, *752*, 141772.
4. Jaspal, S., Aggarwal, A., Verma, T., Kumar, A., Sharma, R., & Devpal, R. (2024). Development of multi-millet edible bowls using little, kodo & barnyard: A sustainable alternative to plastic cups. *Journal of Food Measurement and Characterization*, *18*(8).
5. Kabir, M. H., Hamidon, N., Awang, M., Rahman, M. A. A., & Adnan, S. H. (2022). An Edible Cutleries Using Green Materials: Sorghum Flour. Green Infrastructure: Materials and Applications, 305-317.
6. Khatoniar, S., & Das, P. (2020). Physical and functional properties of some millet varieties of Assam. *Int. J. Curr. Microbiol. App. Sci*, *9*(5), 1508-1515.
7. Nehra, A., Biswas, D., & Roy, S. (2024). Fabrication of brewer's spent grain fortified bio-based edible bowls: A promising alternative to plastic containers. *Biomass Conversion and Biorefinery*, *14*(14), 16425-16434.
8. Sadasivam S & Manickam A. 2023. *Biochemical methods for agricultural sciences*. New Delhi: New Age International (P) Ltd.
9. UNEP 2021, https://www.unep.org/resources/report/drowning-plastics-marine-litter-and-plastic-waste-vital-graphics, accessed on 06.09.2024.
10. Wulandari, T. D., Kinasih, C. P., Syahbananto, G., Listiaji, P., & Ramadhani, N. A. (2023). Characteristics of Edible Bowls Made from Papaya Skin as an Effort to Tackle Plastic Waste in Indonesia. *Journal of Environmental and Science Education*, *3*(2), 119-126.

K. PAPERS PUBLISHED

1. Manivel, D., & Paramasivam, R. (2024). Sorghum spoons enriched with selected edible flowers: A sustainable alternative to conventional cutlery in the food and tourism sectors. *Biomass Conversion and Biorefinery*, 1-14.
2. Devatha, S. M., & Raajeswari, P. A. (2023). Formulation and Quality Assessment of Edible Cups from Sorghum bicolor. *Indian Journal of Nutrition and Dietetics*, *60*(4).
3. Devatha, S.M, & Paramasivam, R. A comparative study on characterization of processed and unprocessed sorghum flours. *The Journal of Research ANGRAU*, *52*(1), 76-84.